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MANNED TEST AND EVALUATION OF MORGAN BREATHING SYSTEM 2000 (MBS 2000) OXYGEN MONITORING SYSTEM

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19. ABSTRACT: The MBS 2000 is an O_2 rebreather intended for O_2 decompression use in a dry chamber. Users purge the breathing loop with O_2 at preset intervals. An O_2 monitoring system (OMS) may reduce the purging needs or indicate needs for more frequent purging. The OMS for the MBS 2000 consists of a sensor (R10-DN) for partial pressure of O_2, but a decision on the need to purge is based on fraction of O_2. Since the water vapor content may be more than 10%, the water vapor present must be considered when conversions are made. An R10-DN is sensitive to temperature and is likely to be somewhat nonlinear at the high partial pressures of O_2 expected. The OMS indicates a sufficient O_2 level by a green light; a red light indicates that purging is needed (switchover at 85%). Manned dives to verify all the functions were required. Twelve military divers participated in the Institutional Review Board–approved manned test of the OMS. Tests lasted 60 minutes at 60 feet of seawater (fsw) and then 60 min at 30 fsw. OMS readings were compared to those of a laboratory-quality O_2 analyzer. Compensations for temperature sensitivity and nonlinearity were made for each R10-DN. Oceaneering (Hanover, MD) and Dive Lab (Panama City Beach, FL) delivered the OMS parts. The average number of purges was 6.2 (range 0–14) in the first 30 min, a level dropping to an average of 2.7 (range 0–5) in the second 30 min period at 60 fsw. At the 30 fsw stop the average was 2.5 (range 0–4.5) purges per 30 min. Data on O_2 from 10 test divers were used. Differences in readings of the OMS and the Rosemont were calculated for each test diver, and the average was –0.01% (range +3.2 to –1.7%). The current purge procedure will not notify users who have a stable inspired O_2 level between 85 and 90%. Adding a time limit will be sufficient. The MBS 2000 OMS worked well, and its readings compared well with those of the O_2 analyzer.

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INTRODUCTION

The MBS 2000 is an O_2 rebreather intended for use in a dry chamber by submariners removed from a pressurized submarine. Currently, MBS 2000 users initially purge the apparatus to attain sufficient O_2 levels in the breathing loop. To maintain a sufficient O_2 level, they must then purge at preset intervals. Having been found to achieve sufficient O_2 levels, this method nonetheless may use more O_2 than necessary. The purpose of this testing is thus to determine whether an added O_2 monitoring system may minimize O_2 usage while maintaining sufficient O_2 levels.

The oxygen monitoring system (OMS) in the MBS 2000 rebreather consists of an O_2 sensor that measures O_2 partial pressure (PO_2), not the fraction of O_2 (FO_2), in the inspired gas. However, a decision on the need to purge is based on FO_2. Therefore, an algorithm was developed to convert the PO_2 reading to an FO_2 reading, including when breathing gas is saturated with water vapor at elevated temperatures (up to 45 °C). The function of this algorithm had been tested in unmanned dives but needed to be tested in manned dives.

A green light on the OMS monitoring unit indicates a sufficient O_2 level. A need to purge is indicated when this light turns red.

METHODS

GENERAL

The Institutional Review Board at Navy Experimental Diving Unit (NEDU) approved the test plan.[1] Before participating, twelve military test divers from NEDU gave written informed consent.

EXPERIMENTAL DESIGN AND ANALYSIS

Depth–time–breathing gas profile

Dives were conducted in a dry hyperbaric chamber to a maximum depth of 60 feet of seawater (fsw; 18 meters of seawater [msw], 2.8 atmospheres absolute [ata]). The profile of time–depth–breathing gas was a shortened version of Schedule III-AB described in a technical report, *Accelerated Decompression Using Oxygen for Submarine Rescue*[2] (Figure 1). After one hour of air breathing at 60 fsw (i.e., the maximum no-stop decompression time), test divers donned the MBS 2000 to breathe O_2. The purpose of this hour of air breathing was to load their nitrogen stores in order to stress the MBS 2000 monitoring system. The test divers breathed on the MBS 2000 for one hour with a 5-minute air break in the middle. They then ascended to 30 fsw. Oxygen breathing continued for another hour before the chamber surfaced. Total oxygen time was thus 2.0 hours. Standard compression and decompression rates (30 ft/min and 60 ft/min) were used.

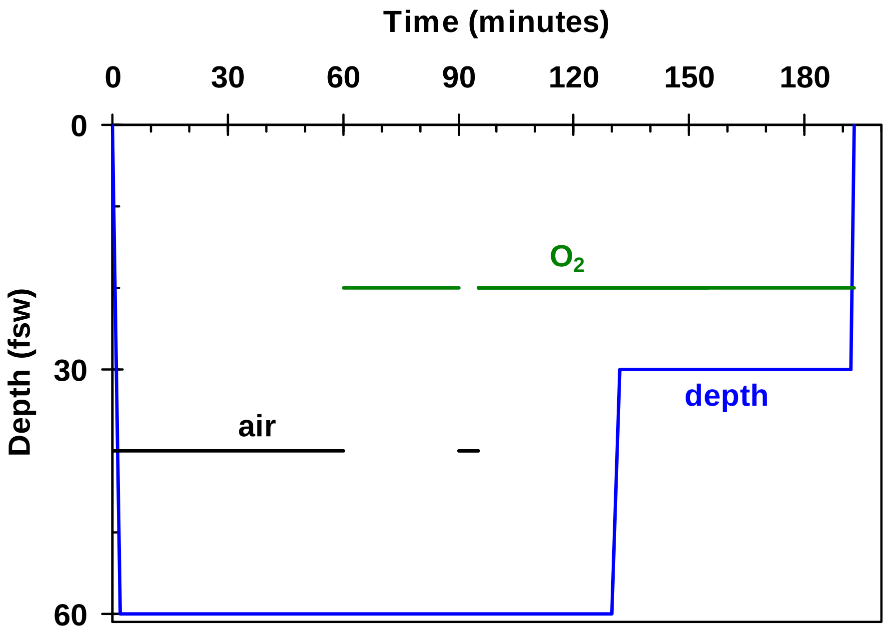

Figure 1. Depth profile and gas usage for evaluating the MBS 2000 oxygen monitoring system.

Estimates of oxygen toxicity risk

The risk of central nervous system (CNS) O_2 toxicity had been estimated two ways, one based on a model by Harabin et al[3] and another based on parts of that model as well as on previous empirical data.[4]

> Estimate 1: The Harabin model — with coefficients for a dry nonexercising dive — estimates the risk of a 30-minute O_2 exposure (90% average inspired O_2 at 60 fsw) to be 0.12% and that of a 60-minute exposure to be 0.41%.
>
> Estimate 2: The empirical data[4] was a collection of 6,250 exposures to 100% O_2 for 30 minutes at 60 fsw (U.S. Navy oxygen tolerance tests). Six episodes of O_2 toxicity were found, an incidence of 0.096%. The Harabin model predicts that the risk increases with (time in hours)$^{1.75}$. Thus, the risk increases by a factor of $2^{1.75}$ = 3.36, to a total risk of 0.096% * 3.36 = 0.32%.

For dry nonexercising dives, the Harabin model has a threshold of 2.4 atm: i.e., the model assigns no risk of O_2 breathing below this threshold. Therefore, the risk at the 60 fsw depth becomes the total estimated risk. The greatest total risk was estimated to be 0.41%.

EQUIPMENT AND INSTRUMENTATION

Drawn continuously from the inspired hose of each test diver, a gas sample was analyzed for its O_2 concentration by a four-channel Rosemont O_2 analyzer that had been tested for absence of influence of humidity. A gas sample had been drawn from O_2 saturated with water at about 40 °C and compared to the reading from a sample drawn from dry O_2. No difference had been found.

Oceaneering (Hanover, MD) delivered the OMS electronics; the remaining hardware was delivered by Dive Lab (Panama City Beach, FL). The temperature and O_2 sensor were read over its own computer network with a LabVIEW program written in-house. This program was set to turn the green light to a red light if the inspired FO_2 decreased to less than 85% for more than about 30 seconds.

The temperature sensitivity of each O_2 sensor used was determined by taking the O_2 readings at two temperatures in the range that the sensors were expected to experience (22–46 °C). Thus, the reading from a temperature sensor was used to correct an O_2 sensor reading on the basis of actual temperature.

The linearity of each R10DN O_2 sensor had been determined by exposing it to O_2 pressures up to 3.0 atm. The readings used in the data analysis were corrected for these known errors. The sensors were calibrated daily by being exposed to 100% N_2 and then 100% O_2 while their readings were noted.

Each O_2 sensor was placed in its holder so that the sensing surface faced away from the gas stream, so that any condensation from the warm, moist gas would not block the sensing surface.

The CO_2 scrubber was filled with Sofnolime 812 NI D grade absorbent (Molecular Products).

<u>Converting PO_2 to FO_2</u>

When readings are converted from PO_2 to FO_2, the presence of water vapor must be considered. Since the water vapor pressure depends only on temperature, it does not follow the normal laws for ideal gases. The water vapor pressure can be calculated from the following equation:[5]

$$P_{H_2O} = e^{(A - B/(T+C))}$$

where A = 18.6686, B = 4030.183 K, C = 235 K, and T is the temperature in °C. P_{H_2O} is in Torr and is claimed to be accurate to within 0.05 Torr over the range 0–50 °C.

The determination of the FO_2 should be in the dry part of the gas. Total pressure ($P_{chamber}$), O_2 sensor reading, and temperature are known.

The conversion from PO_2 to FO_2 was done in steps:

1. The temperature at the R-10DN sensor was measured.
2. The PH_2O was calculated.
3. The pressure of the dry gas was calculated as $P_{dry} = P_{chamber} - PH_2O$.
4. The FO_2 was calculated as $FO_2 = PO_2/P_{dry}$.

As an example, assume that the depth was 10 fsw (3 msw, 1.30 ata, 132 kPa), that the R10DN read a PO_2 of 1.08 atm and that the temperature was 48 °C (118 °F). The PH_2O was calculated to be 0.11 atm. The dry part of the gas mixture (P_{dry}) was 1.30 – 0.11 = 1.19 atm. The FO_2 was 1.08 / 1.19 = 0.91 — i.e., 91%. Had the water vapor been ignored, the reading would have been 1.08 / 1.30 = 0.83 — i.e., 83% instead. To omit a correction for water vapor would have introduced a significant error.

PROCEDURES

Before the tests, each diver was fitted with a mask that sealed well on the face. Each diver was trained how to purge when it was indicated. Four test divers entered the chamber, which was pressurized to 60 fsw (2.8 ata). After 60 minutes the test divers donned the MBS 2000. As needed, a tender assisted with fitting the mask. Each test diver then switched the rig to open circuit and took five deep breaths to initially purge the MBS 2000. An adequate O_2 level was indicated once the OMS light turned from red to green. For the duration of the dive, if the OMS light turned red, the test diver would go open circuit and purge the MBS 2000 by taking three deep breaths to raise the O_2 level.

The signals from each temperature and O_2 sensor were recorded and plotted continuously on a computer screen. The inside tender alerted a test diver if the light had been red for more than some 20 to 30 seconds.

RESULTS

Data from 12 test divers were obtained. No sign of O_2 toxicity was apparent.

The information from the OMS could be read as desired, and the red/green light worked properly in indicating the need to purge as required. Due to the instability of one channel on the Rosemont O_2 analyzer, two data points had to be omitted. Before the third dive, the faulty channel was replaced. Thus, data from 10 test divers were in the analysis.

The response time of the R10DN O_2 sensor and network was different from that of the Rosemont analyzer with its gas sample lines. The difference in timing was determined from the sudden changes in O_2 readings when a test diver purged. The time difference was determined at both 30- and 60-foot depths. After the time correction was applied, the difference between the two O_2 readings was calculated.

The sensitivity to temperature was determined by measuring each sensor's reading in air at three temperatures: 22, 30.5, and 46.5 °C. The average temperature sensitivity was 0.47% per °C. Each reading from an R10DN sensor was corrected for the known sensitivities to temperature and nonlinearity.

Changes in O_2 levels during the tests

Figures 2 and 3 both illustrate results from two separate test divers, on different dives. Figure 2A shows that the test diver needed several purges in the first five minutes of the test. The purging need slowed in the next five-minute period, followed by one more in the next 15 minutes. After the air break, six purges were needed while the diver was at 60 fsw. An additional three purges were needed during the 60 minutes at 30 fsw. Figure 2B shows that the OMS underestimated the O_2 values slightly early in the test and read essentially the same as the Rosemont while the diver was at 30 fsw. The occasional spikes in the differences are due to inexact time corrections for the two O_2 measurements.

Figure 3A shows that the test diver needed two purges (around minute 10) to maintain a stable O_2 level. After the air break, only one more purge (minute 115) was needed. Figure 3B shows that the OMS underestimated the O_2 values slightly early in the test and overestimated the O_2 values slightly after two hours. The occasional spikes in the differences are due to inexact time corrections for the two O_2 measurements. Figure 3A also shows that the test maintained an O_2 level between 85 and 90% for the entire 60-minute period at 30 fsw.

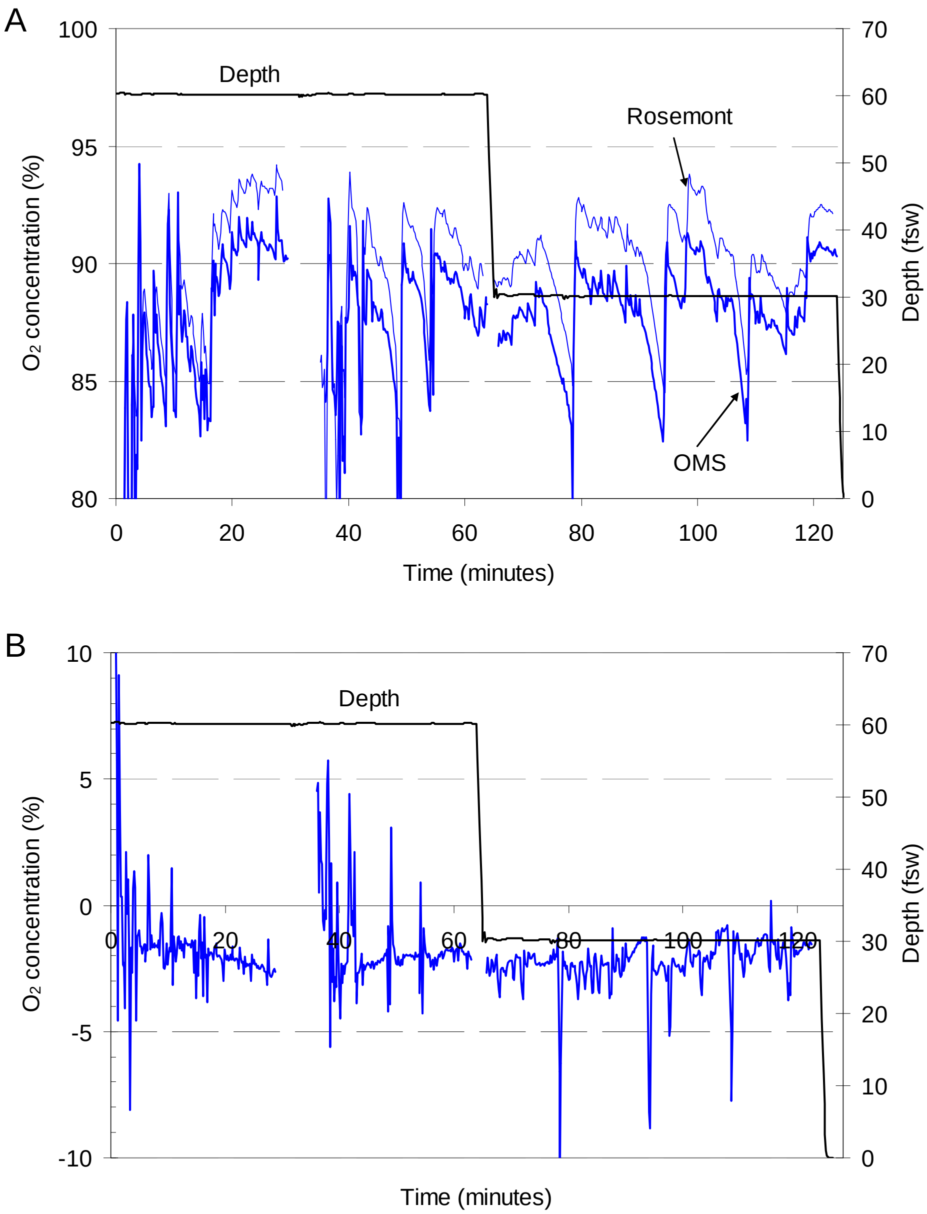

Figure 2. Panel A shows the depths and the recordings from the OMS and the Rosemont O_2 analyzer. Panel B shows the depths and the absolute differences between the two O_2 values. The gap in O_2 readings between minutes 30 and 35 is due to the air break.

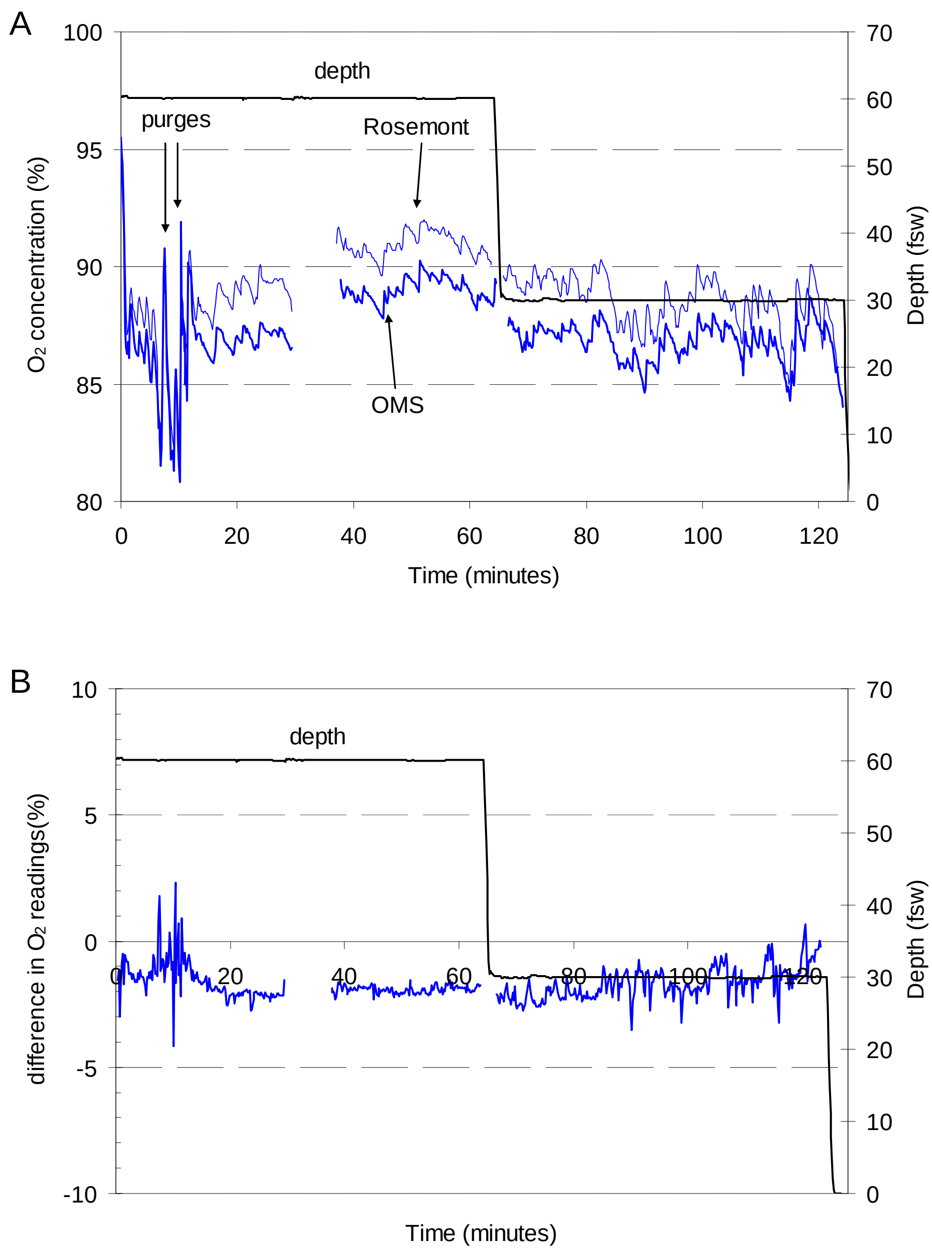

Figure 3. Panel A shows the depths and the recordings from the OMS and the Rosemont O_2 analyzer. Panel B shows the depths and the differences between the two O_2 values. The gap in O_2 readings between minutes 30 and 35 is due to the air break. The OMS unit is the same as in Figure 2, but the test diver and day of testing are different.

Frequency of purging

The number of purges needed to maintain adequate O_2 is illustrated in Figure 4. In the first 30-minute period at 60 fsw the number varied from 0 to 14 purges, with an average of 6.2 purges. Test divers who sat quietly tended to need fewer purges than those who moved around; the latter divers needed the most purges. During the second 30-minute period the number of purges decreased: it varied from 0 to 5, with an average of 2.7. During the 60-minute long stop at 30 fsw, the number of purges varied from 0 to 4.5 per 30-minute period, with an average of 2.5 purges per period.

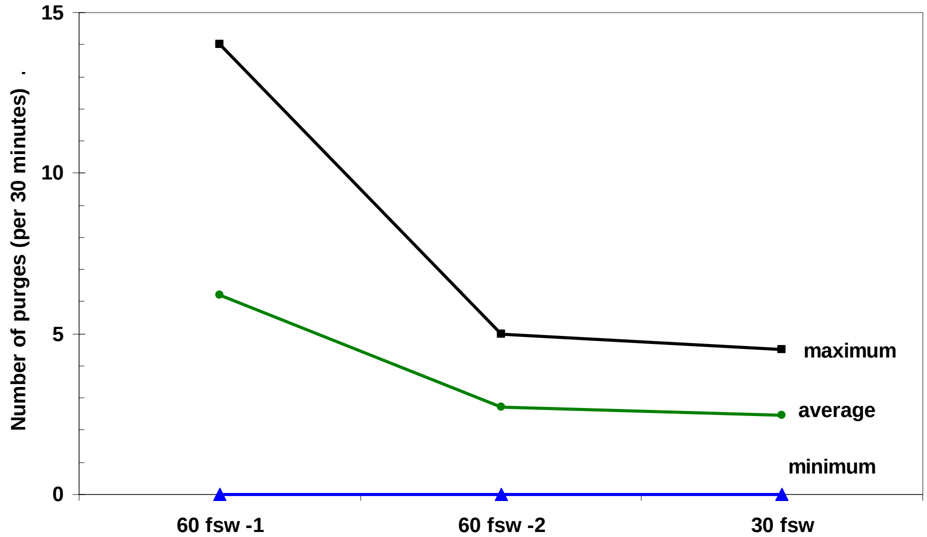

Figure 4. The number of purges needed to maintain a desired O_2 level. The values are expressed as purges per 30-minute period.

Differences between the readings of O_2

The differences in the OMS and the Rosemont readings were calculated for each test diver. The average difference was –0.01%, with a range of +3.2 to –1.7%.

DISCUSSION

The readings from the OMS compared very well to those from the Rosemont analyzer.

Figure 3A shows that the current procedure of purging when the O_2 level is below 85% may not identify people who have a good mask seal. Their O_2 levels can remain constant, and they do not have to purge. Simply adding a time limit — i.e., an alert when the O_2 has been less than 90% for a certain length of time — will alert these people to the need to purge.

For some people the purge frequency was high early in the test, but this frequency decreased as the dive progressed. Rapid head movements seemed to accompany an increased need to purge. Perhaps the breathing hoses gave enough of a pull on the mask to cause a sufficient leak.

Even though the R10DN O_2 sensors are listed as being temperature corrected, they still showed a temperature sensitivity of about 0.5% per °C. If the temperature seen during use differs from the calibration temperature, then a large error can be expected. It is common to see that a CO_2 absorber raises the temperature by 20 °C. Depending on the user's minute ventilation, the temperature may not start to increase until 20 to 40 minutes after the breathing has started. For this application, where the sensor is very close to the scrubber outlet, the temperature will be elevated above ambient temperature. Therefore, it is essential to know the magnitude of, and to correct for, this temperature sensitivity.

The influence of the water vapor is also significant: at a high temperature (45 °C, 118 °F) the water vapor content is about 10% of the gas composition at 1 ata. Therefore, the water vapor must be included when conversions are made from PO_2 to FO_2

CONCLUSIONS

The readings from the MBS 2000 OMS compared very well to those of the Rosemont gas analyzer. Corrections for water vapor content, nonlinearity, and temperature sensitivity must be made.

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